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ABSTRACT:

The decay of both wind- and paddle-generated surface capillary-gravity waves passing through a zone of turbulent water was measured. The results point to a dissipative decay mechanism that is proportional to wave amplitude squared, with a proportionality constant which varies as frequency to the fifth power.

This task was supported by: University of Wisconsin Sea Grant Program
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SOME MEASUREMENTS OF SURFACE-WAVE DECAY DUE TO UNDERWATER TURBULENCE

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ABSTRACT

The decay of both wind- and paddle-generated surface capillary-gravity waves passing through a zone of turbulent water was measured. The results point to a dissipative decay mechanism that is proportional to wave amplitude squared, with a proportionality constant which varies as frequency to the fifth power.

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I. INTRODUCTION

Compared with mechanisms for the growth of water waves, those for wave decay have received little attention. In wave forecasting, for example, there is far more agreement on empirical wave growth formulas than on decay formulas. In the case of decay due to ambient ("external") underwater turbulence, the relative neglect is probably due to the lack of both ocean turbulence data and a simple theory. That of Phillips (1959) is based on the turbulence spectrum near a free surface, which has not been studied in detail. Earlier, more speculative work (Groen, 1954; Bowden, 1950) is also closely tied to unknown characteristics of the near-surface turbulence.

However, wave decay is quite important, and the results of the simple but novel laboratory experiment described below provide some insight into this problem. These results are admittedly fragmentary: the experiment was preliminary in nature, and the work had to be abandoned unexpectedly. Nevertheless, it seems worthwhile to present our data and tentative conclusions to guide others in similar work.

II. APPARATUS

A paddle (or fan) generated surface waves which propagated down a long tank, over a zone of underwater turbulence, to a non-reflecting beach (Fig. 1). The turbulence was produced by a vertically oscillating underwater grid, which spanned the width of the tank, and consisted of 1.-cm wide metal strips woven about 1.-cm apart so that the energy containing eddies had a scale of 1. cm

(see Paquin, 1968, for details). The oscillation frequency was approximately 1. Hz; the amplitude was 1. cm. The eddies had little direct effect on the water surface. The waves produced by turbulence alone were less than a millimeter in height, whereas the paddle- or wind-generated wave heights were on the order of centimeters upstream of (i.e., before entering) the turbulent region. No wave breaking was observed.

Surface waves were shielded from mean currents caused by the grid drive mechanism by a false bottom (Fig. 1). Any such current remaining was completely masked by the velocity fluctuations, so that the effect of wave-current interactions was probably quite small. Wave frequencies ranged from 1 to 10 Hz. Frequencies above 2 Hz corresponded to deep-water waves (Stoker, 1957), so that the influence of both bottom and grid was negligible. For lower frequencies the false bottom was removed (introducing weak currents not otherwise present) but the waves did feel the grid itself. Faraday waves (McGoldrick, 1968) were suppressed by thin metal strips near the paddle.

Resistance wave gauges were mounted upstream and downstream of the turbulent zone, and were calibrated both statically and dynamically (using progressive waves and stroboscopic light). The response was flat from DC to 4 Hz and 10% down at 26 Hz. A constant-temperature anemometer (DISA Model 55A01) was used with a quartz-protected hot-film probe (DISA 55A81) to measure the turbulent motions. All data were FM recorded with a Precision Instruments 6200 Tape Recorder and analyzed, after playback at 10 times or 100 times the recording speed, with a General Radio Type 1900 Wave Analyzer.

III. MEASUREMENTS

All measurements were made during steady conditions with clean tap water. The decay due to viscosity and possible surface films was determined first, then (immediately afterward) that due to these causes plus turbulence.

A typical paddle-generated wave spectrum (with or without turbulence) is shown in Fig. 2. In order to investigate the widths of the harmonics, the recorder playback speed and the analyzer bandwidth were varied to produce an effective bandwidth that ranged from 1.0 Hz to 0.1 Hz. Since the observed energy level did not depend on the bandwidth, the wave energy was assumed to be located only at the paddle frequency and its harmonics, and results were interpreted as line spectra. Figure 3 shows typical line spectra in the presence of turbulence.

The turbulence velocity spectrum obtained with the anemometer placed in the center of the turbulent region at a depth of 2. cm, is shown in Fig. 4. Similar spectra were found at depths of 1. and 3. cm at various positions in the region. The lack of a large superimposed unidirectional flow introduced serious problems associated with variations of probe sensitivity with flow direction. Calibration showed the minimum sensitivity to be about 25% of the maximum. (The hot-film probe was always set to be most sensitive to flow in the wave propagation direction.) Thus, the turbulence spectrum should be interpreted in a qualitative sense, showing only that the spectral peak is below the wave frequencies, and giving some indication of the turbulence intensity.

A corresponding velocity spectrum due to paddle waves alone is also shown in Fig. 4. Despite the sensitivity problem, the peaks associated with the paddle waves dominate, and the energy associated with the fundamental wave is within a factor of two of that predicted by linear theory.

Within the interacting region the turbulence energy is comparable to the wave energy. This is convenient for the experiment since large (hence easily measured) wave decay results. On the other hand, it probably does not reflect conditions in a natural environment, where wave motions are expected to dominate (Shonting, 1968).

IV. DISCUSSION

A. Paddle-generated Waves

According to laminar viscous theory for surface waves (Van Dorn, 1966), wave decay with distance is given by the linear expression

$$da/dx = -\beta_\ell a$$

which gives

$$a(x) = a(x_o)\exp\{-\beta_\ell(x - x_o)\}. \qquad (1)$$

Here, a is wave amplitude, x is propagation distance, and β_ℓ, the damping coefficient, varies with frequency f, viscosity, and the character of any surface film present. This is a first-order result in ka (k is wave number), valid for ka<<1. The measured ka values ranged from 0.04 to about 1; most were near 0.5.

Nevertheless, we use (1) to determine β_ℓ. In no case was the observed laminar decay greater than could be explained by the presence of a surface film.

Following Phillips (1959), two turbulent mechanisms can lead to wave decay. Scattering (due to turbulent convective distortion of wave fronts) is a first-order process in ka, results in the generation of a broad spectrum of scattered waves, and leads to an exponential decay law analogous to (1) with β_ℓ replaced by β_t. Phillips' results can be rewritten to show that two-dimensional waves passing through a horizontally homogeneous turbulent region experience scattering losses giving $\beta_t \propto f^{8/3}$.

Dissipation (whereby mean wave motions strain turbulent vortex filaments, thus increasing turbulent energy at the expense of wave energy) is a second-order process in ka, which is effective when the scale of the turbulence is much less than that of the waves. The decay law associated with this mechanism is not known, but is probably nonlinear in wave amplitude (in the differential form).

It is likely that dissipation dominated in this experiment for the following reasons: (1) the mean square surface height downstream of the turbulent zone was typically less than 10% of that upstream. (2) Any decay due to scattering should be accompanied by a broadening of the downstream wave spectrum; we could not detect any broadening with our filters. (This supported the observation that the downstream waves continued to appear long-crested.) (3) Finally, scattering should cause random fluctuations

in the contribution of any fixed frequency band to the rms surface height, as read on the wave analyzer voltmeter. (Note that the tank walls were smooth, allowing good reflection, so that wall effects on scattering should be slight.) Fluctuations of about 10% of the mean value were observed downstream; they were undetectable upstream. Therefore, scattering accounted for a very small fraction of the total energy lost by the incident wave.

B. Wind-generated Waves

Wind waves generated in the laboratory obey an exponential growth law (Hidy and Plate, 1966)

$$da/dx = \beta_w a.$$

Since both the growth due to wind and the laminar decay follow an exponential law, they can be combined to give an effective β_ℓ in (1) (which may no longer be positive).

The energy is now broad band. Measurements and calculations were done using energy in 1.- Hz bandwidths. The results are plotted against the center frequency of the filter band.

IV. INTERPRETATION OF RESULTS

The decay measurements are interpreted in two ways.

A. Linear Decay Hypothesis

Figure 5 shows the effect of assuming a linear turbulent decay process (such as would occur with scattering), which is independent of laminar decay:

$$da/dx = -(\beta_\ell + \beta_t)a$$

or

$$a(x) = a(x_o) \exp \{-(\beta_\ell + \beta_t)(x - x_o)\}. \qquad (2)$$

The observed decay with no turbulence gives β_ℓ (eqn. 1); the corresponding decay with turbulence then gives β_t.

The fundamentals travel as free waves. The second harmonics are not free waves, but bound waves associated with a periodic nonsinusoidal profile (Lamb, Art. 250). We are interested in the decay of free waves. A reasonable correction is to plot the second- harmonic turbulent damping coefficients against the frequency of free waves of the same wave number. In the same spirit this correction is based on linear theory. (Aside from some third-order work by Wilton, 1915, there are no nonlinear dispersion results for capillary-gravity waves.) A free wave obeys the dispersion law

$$4\pi^2 f^2 = gk + Tk^3/\rho \qquad (3)$$

where g is gravity, ρ density, and T surface tension. Since the second-harmonic wave numbers and frequencies are double those for the first harmonic, the actual dispersion law for the second harmonics is

$$\pi^2 f_2{}^2 = gk_2/2 + Tk_2{}^3/8\rho.$$

Then the corrected second-harmonic frequency is

$$(f_2)_{corr} = \left[\frac{1 + Tk_2{}^2/\rho g}{2 + Tk_2{}^2/2\rho g}\right]^{1/2} f_2 .$$

All second-harmonic damping coefficients are plotted at their corrected frequencies.

The paddle-wave results can be fitted to the power-law relation

$$\beta_t = cf^2$$

where c_1 is $3.2 \times 10^{-3}\ \sec^2 \mathrm{cm}^{-1}$ (first harmonics), and c_2 is $1.8 \times 10^{-3}\ \sec^2 \mathrm{cm}^{-1}$ (second harmonics). Based on the reasoning given above, we view the reasonable agreement with Phillips' 8/3-power prediction as accidental. Also, Phillips' result rests on a model which is quite unlike the experiment: surface tension is neglected; the incident wave (already assumed small: $ka \ll 1$) is tàken to vary little over the time of the decay calculation; the turbulence spectrum is fixed on dimensional reasoning based on the existence of an inertial subrange. All of these assumptions are violated here.

The discrepancy between values of c for the first two harmonics suggests either an energy transfer between the harmonics or, since the first harmonics are stronger than the second, that there is an amplitude dependence hidden in the damping coefficient β_t. McGoldrick (1965) has shown that long-crested capillary-gravity waves do experience a resonant interaction between the first and second harmonics near the fundamental wave number $K = (g/2T)^{1/2}$ ($2.6\ \mathrm{cm}^{-1}$ for pure water at 20°C). For measured values of T, however, K was far above the experimental wave numbers, so that resonance was highly unlikely.

B. Quadratic Decay Hypothesis

The alternative explanation for the discrepancy between the first- and second-harmonic damping coefficients is explored by assuming (somewhat arbitrarily) a quadratic decay law, such as might be expected with turbulent dissipation, adding to the linear laminar decay:

$$da/dx = -(\beta_\ell a + \gamma_t a^2) \tag{4}$$

or

$$a(x) = \frac{a(x_o)\ \exp\{-\beta_\ell(x - x_o)\}}{1 + \frac{\gamma_t a(x_o)}{\beta_\ell}[1 - \exp\{-\beta_\ell(x - x_o)\}]}. \tag{5}$$

The observed turbulent decay and eqn. 5 give γ_t. The results are shown in Fig. 6. Although there is still some scatter, a more consistent picture has emerged. Aside from two questionable experimental points (common to both hypotheses), all points can be fit to the power-law relation

$$\gamma_t = Cf^5 \tag{6}$$

where C is $1.7 \times 10^{-5}\ \sec^5 cm^{-2}$.

On the basis of this evidence, we suggest that steep capillary-gravity waves in the presence of underwater turbulence obey a dissipative decay law which is close to quadratic (i.e., eqn. 4) when

(i) the length scale of the turbulence is much less than the wave length

(ii) the energy per volume of the turbulence is the same order as the maximum energy per volume of the waves.

V. ACKNOWLEDGEMENT

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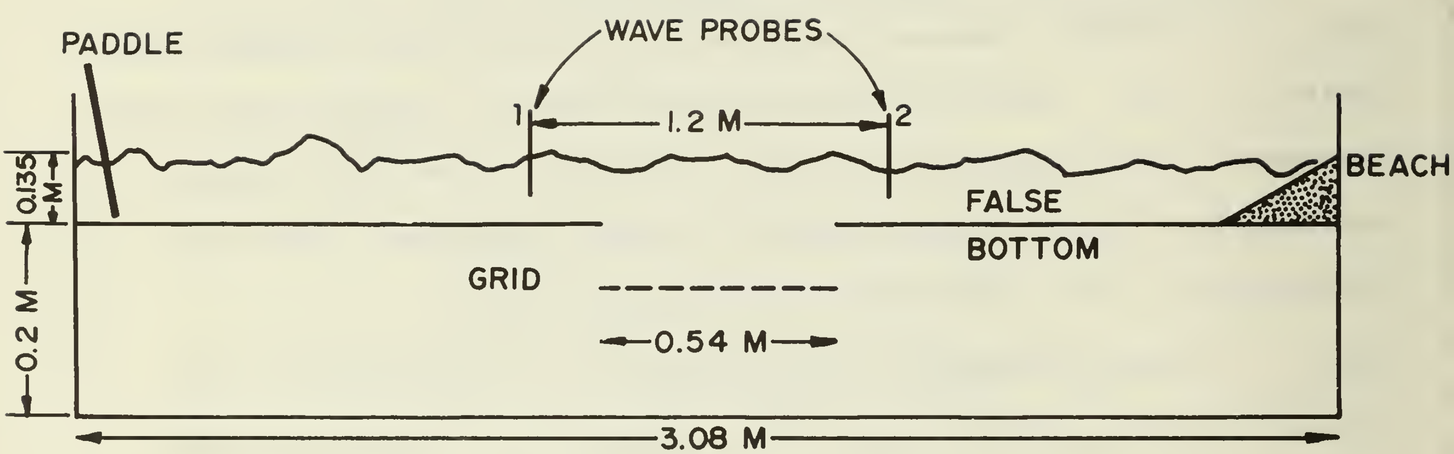
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2
BEACH
0.135 M
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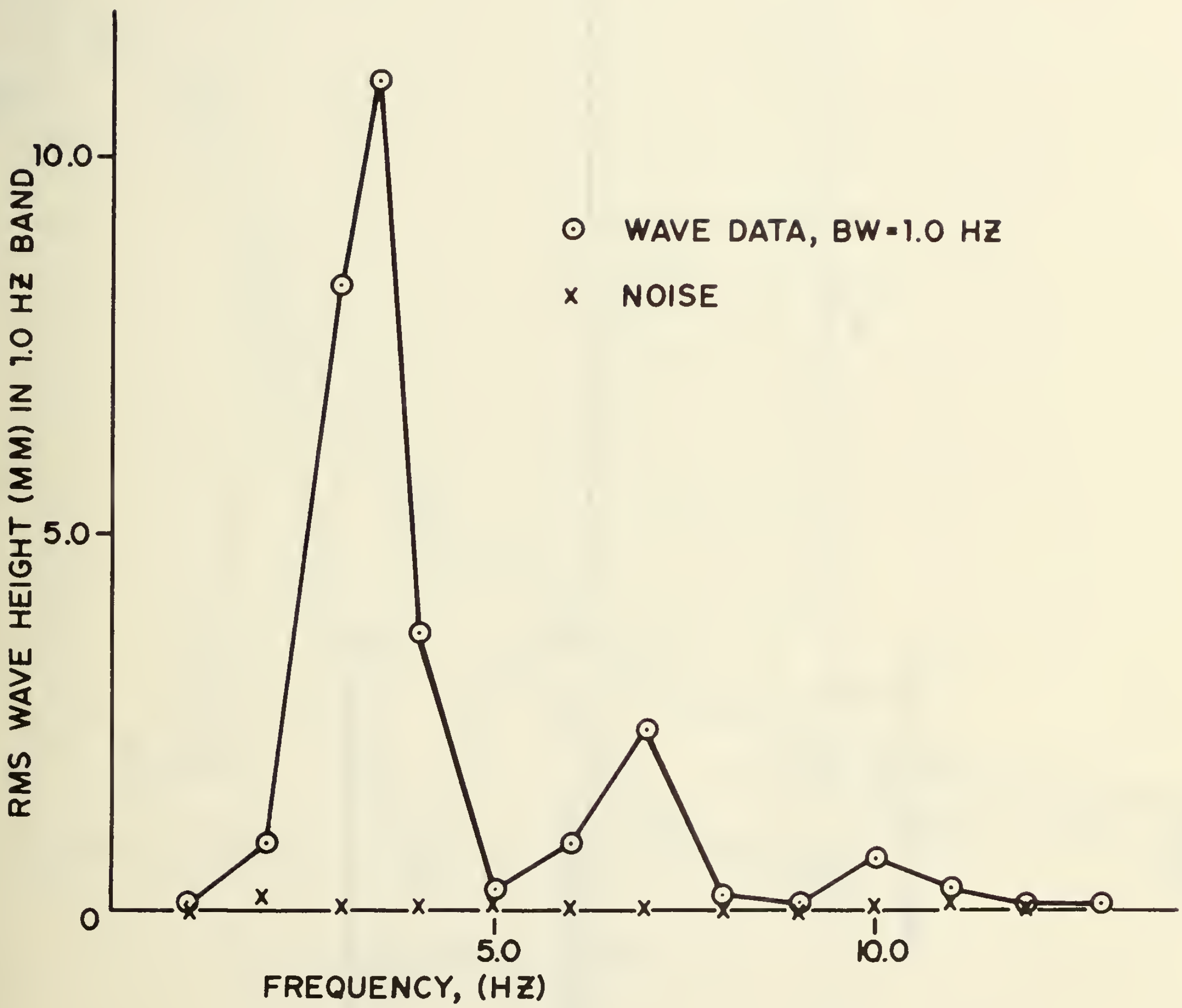
BOTTOM
GRID
0.2 M
0.54 M
3.08 M

NOT TO SCALE



RMS WAVE HEIGHT (MM) IN 1.0 HZ BAND
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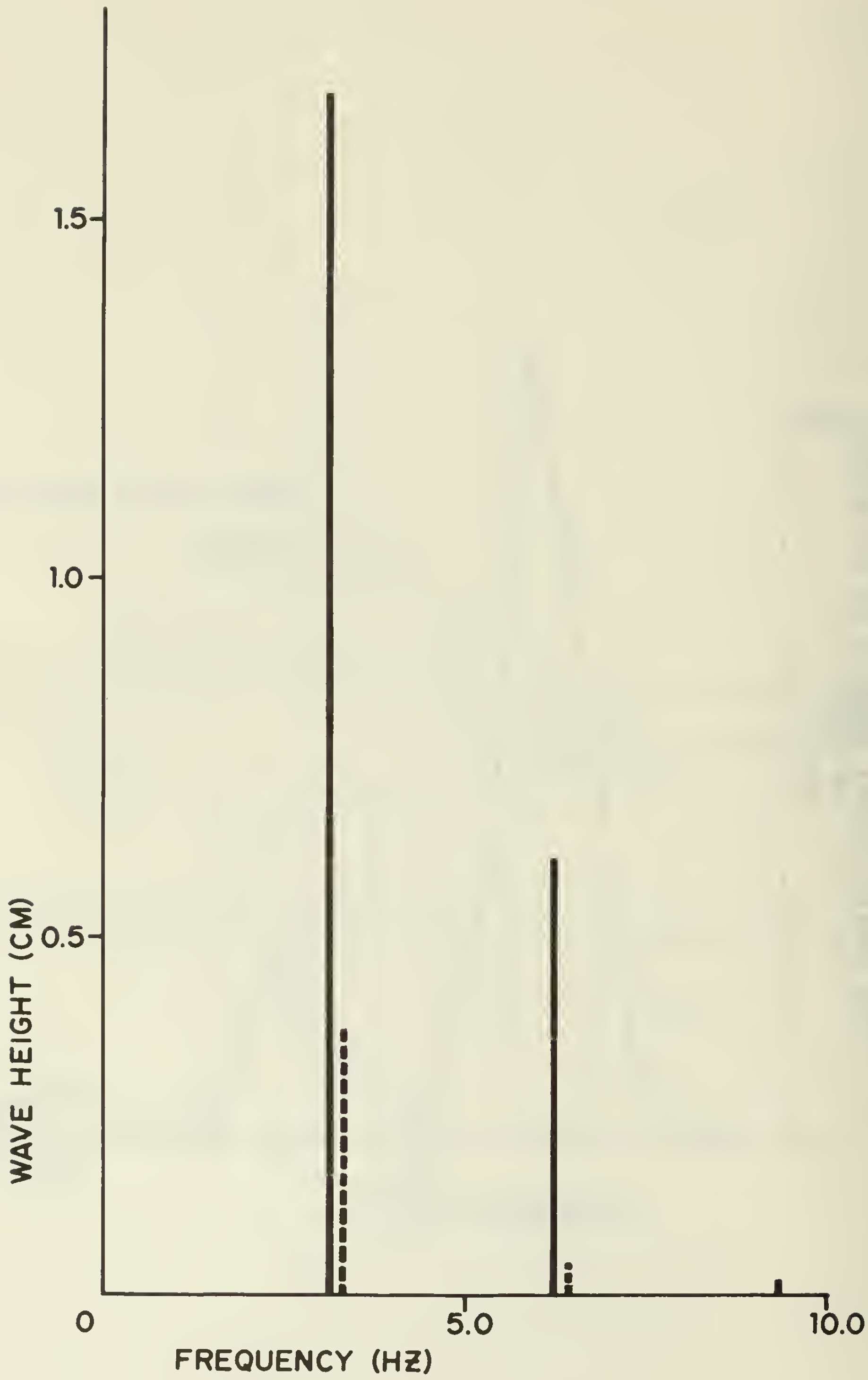
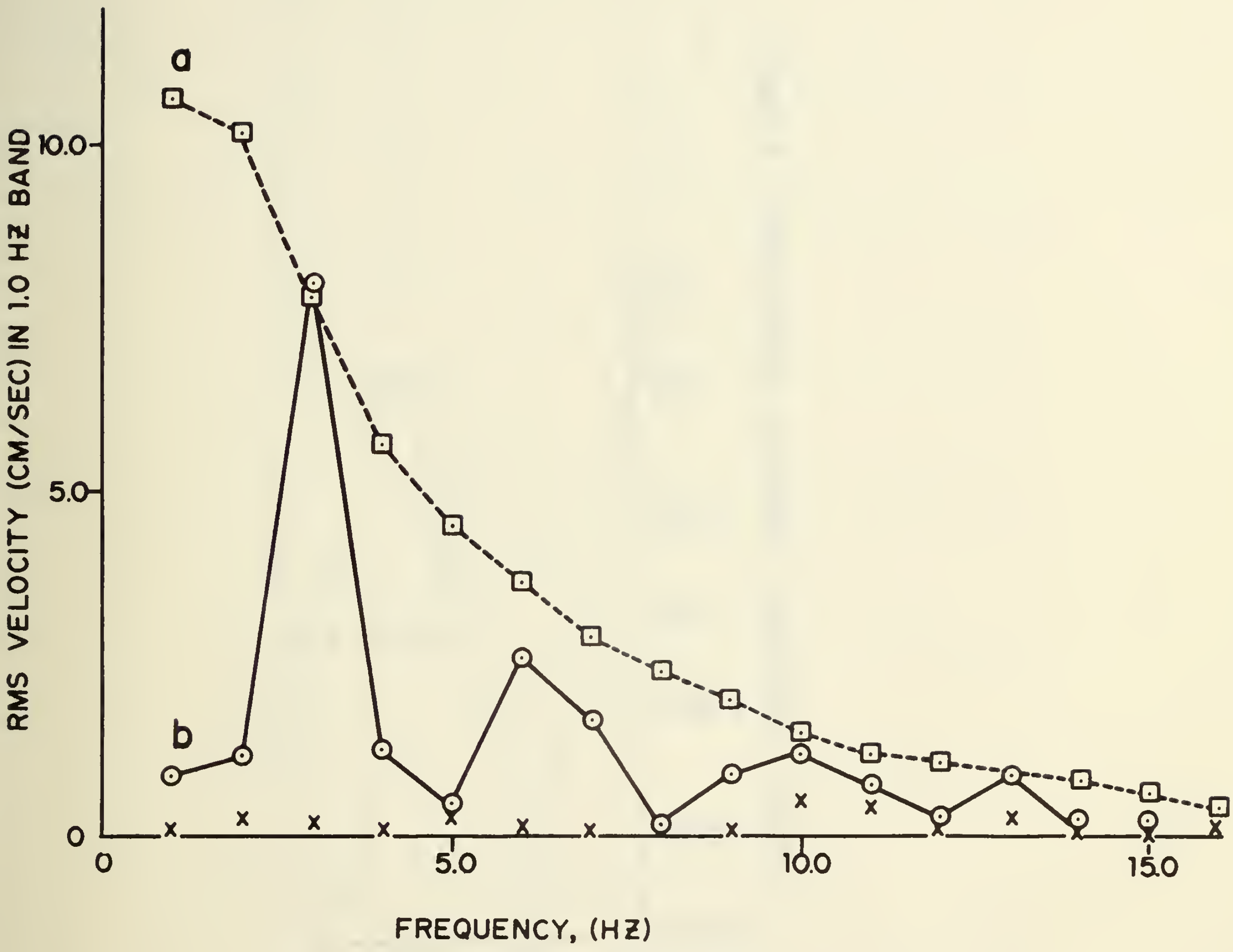
WAVE DATA, BW=1.0 HZ
NOISE
5.0
10.0
FREQUENCY, (HZ)



1.5
1.0
0.5
WAVE HEIGHT (CM)
0
5.0
10.0
FREQUENCY (HZ)



a
b
RMS VELOCITY (CM/SEC) IN 1.0 HZ BAND
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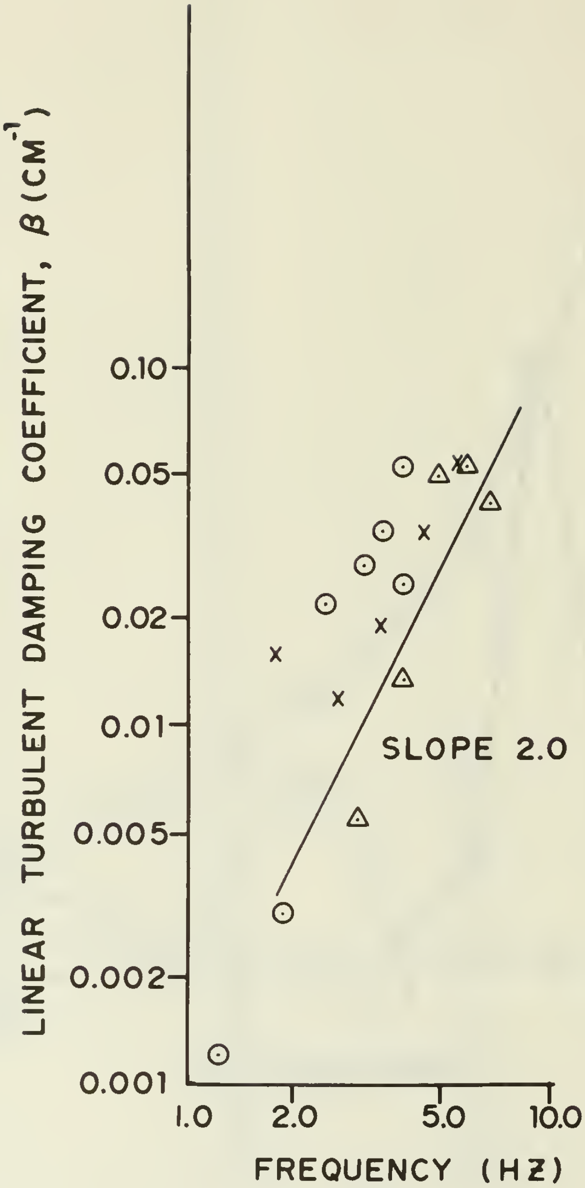
5.0
0
0
5.0
10.0
15.0
FREQUENCY, (HZ)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0.02
0.01
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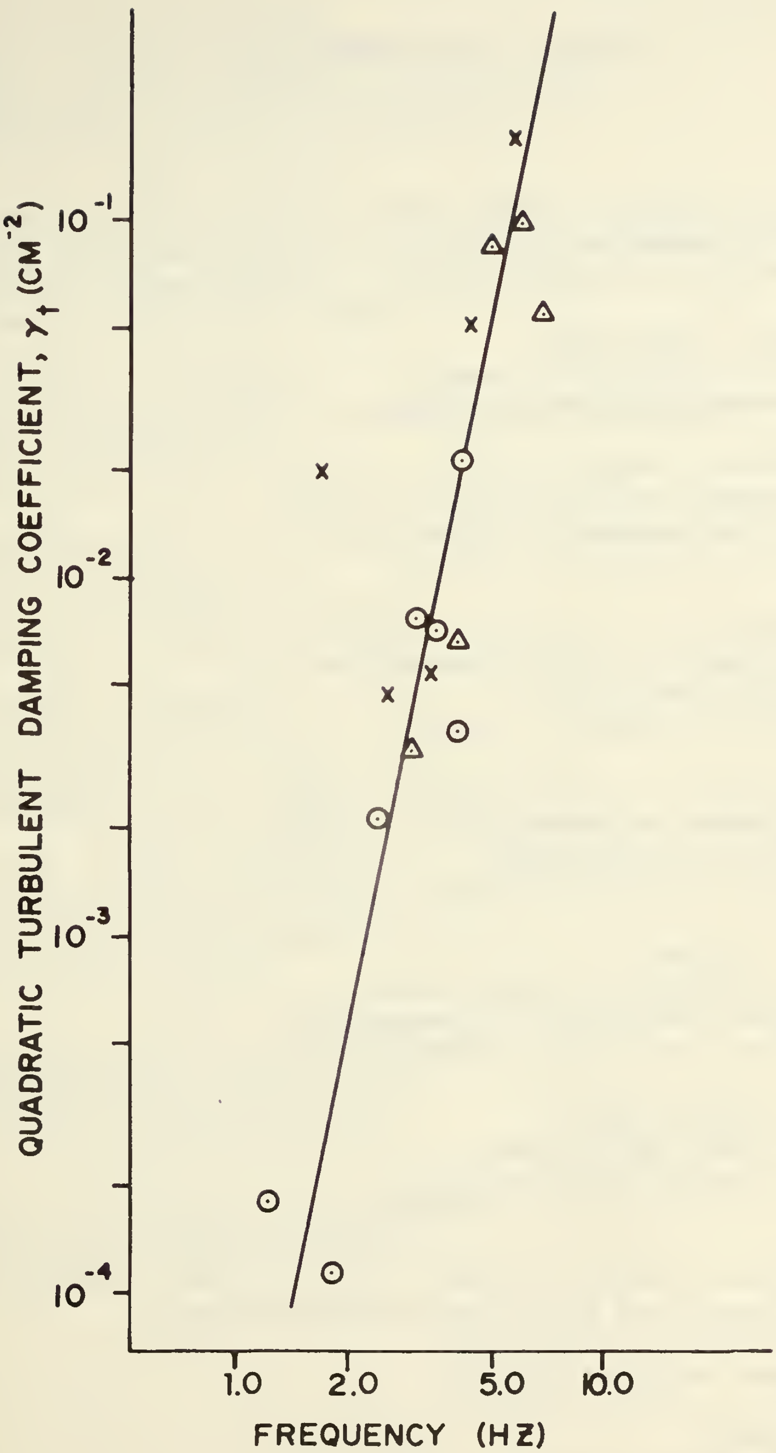
0.002
0.001
1.0
2.0
5.0
10.0
FREQUENCY (HZ)
SLOPE 2.0



QUADRATIC TURBULENT DAMPING COEFFICIENT, γ_t (CM^{-2})
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10^{-2}
10^{-3}
10^{-4}
1.0
2.0
5.0
10.0
FREQUENCY (HZ)

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